# THOR ADVANCED TEST DUMMY - BIOFIDELITY AND INJURY ASSESSMENT

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## ABSTRACT

This paper will discuss the advances in biofidelity and injury assessment provided by the THOR Frontal Crash Test Dummy, particularly in regard to use by the aircraft safety industry. Following a brief background on the THOR development project, injury data from the Kegworth crash in 1989 will be presented to exemplify the specific types and severity of injuries which may occur in a commercial airline crash. Based on this injury data, five specific regions of the dummy (face, neck, lower abdomen, pelvis - femur, and lower extremities) will be discussed in detail. The biomechanical background, mechanical design and instrumentation will be discussed for each region of the dummy. Additionally, a series of THOR impact test data will be presented to show the biofidelic response of the lower abdomen and femur - pelvis - knee assemblies to impact forces.

## INTRODUCTION

For several years the National Highway Traffic Safety Administration (NHTSA) has actively supported the development of an advanced frontal crash test dummy that incorporates improved biofidelic features and significantly expanded instrumentation. This development program, undertaken by GESAC Inc approximately four years ago, has resulted in the design and development of a test device for whole-body trauma assessment in a variety of occupant restraint environments. **Figure #1** shows a picture of the new advanced frontal crash test dummy which has been named THOR (Test Device for Human Occupant Restraint). Currently, two dummies have been fabricated and are undergoing evaluation by means of full scale sled and vehicle testing. The primary design objectives of the development effort were as follows:

Biofidelity in mass, size, surface geometry, and dynamic response

Incorporation of specific instrumentation relevant to injury assessment

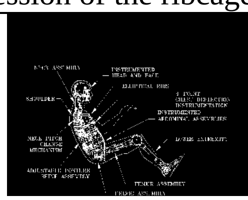
Repeatability of performance
Minimization of damage in severe test environments; i.e., overload protection

User friendliness and modularity in design, for ease of assembly and disassembly


**FIGURE 1**

The approach undertaken during the design of the THOR dummy was to first review the design elements which had been incorporated in the TAD-50M (the NHTSA funded predecessor to the THOR dummy). This review was conducted to identify needed improvements in biofidelity, dynamic response, and instrumentation. A systematic evaluation of design requirements for each body region was then accomplished. The design of THOR resulted in improvements to all the dummy components except the arms (which remain Hybrid III stock pending conclusion of arm development efforts ongoing within the automotive industry).

**Figure #2** presents an assembly drawing of THOR indicating its primary new features. The facial region of the dummy has been instrumented with unidirectional load cells to assess the probability of facial fracture. The THOR neck assembly features multidirectional kinematic biofidelity, which results in more accurate head trajectories, velocities and accelerations for front, side and rear impacts. The thorax region utilizes elliptical ribs whichgreatly enhance the biofidelity and geometry. In addition, a new thorax deflection sensor has been designed which measured the dynamic three dimensional compression of the ribcage at four distinct points. A



newly designed abdominal segment can directly measure belt intrusion in three dimensions at two distinct points. The pelvis has been instrumented with a three axis acetabular load cell at each hip joint and belt load sensors on each Iliac notch. The THOR femur assembly includes a compliant element to provide the correct force transmission for axial loading through the femur into the pelvic assembly. A new lower extremity has been developed which provides increased injury sensing capabilities in the foot, ankle and lower leg, as well as, greatly improving the torque vs. angle relationship for the primary ankle rotation joints. In addition, the THOR dummy features many advances in sensors and instrumentation and is capable of measuring over one hundred channels of data for injury assessment. This paper will focus on five regions of interest which may be of particular interest to the aircraft safety industry: the face, the neck, the lower abdomen, the pelvis - femur assembly, and the lower extremities.

## THE KEGWORTH CRASH - INJURY AND TRAUMA ASSESSMENT

As an example of the types of injuries a passenger may receive in a commercial airline crash, the Kegworth crash from 1989 will be cited since the medical and pathological data was well documented and described in detail by the Air Accidents Investigation Branch (AAIB) of the Department of Transport, U.K.. The Boeing 737 suffered engine trouble shortly after leaving Heathrow Airport for Belfast and crashed while attempting to make an emergency landing. There were one hundred eighteen passengers and eight crew on board the aircraft. A total of forty seven passengers died as a result of the accident, seventy nine passengers and crew survived. The specific types of injuries are presented to illustrate the type of injury and trauma sensing capabilities which should be present in a test device used for aircraft safety research. The following medical and pathological information was taken directly from the Air Accidents Investigation Branch - Aircraft Accident Report No. 4/90 (EW/C1095) (August 1990).

> Head / Facial injury -All but one of the thirty nine fatalities at the scene of the accident sustained head injuries of varying severity. Forty three non-survivors had facial injuries. Seventy four of the eighty three patients removed to hospital had suffered head or facial injury. Thirty one cases of facial injury required treatment.

Neck injury - Twenty one non-survivors and six survivors sustained injuries to neck structure.

Upper limb and shoulder injury - Nineteen fatalities and twenty eight survivors sustained fractures and dislocations of the upper limbs and shoulders.

Chest injury - Some degree of generally major chest injury was found in all but one of the fatalities. Eighteen of the seventy nine survivors also suffered major chest trauma.

Abdominal injury - Thirty six fatalities suffered abdominal trauma compared to only two of the survivors who suffered a major abdominal injury.

Pelvis / Femur / Knee injuries - Twenty two survivors and thirteen non-survivors sustained pelvic injuries. Twenty two survivors and thirteen non-survivors sustained fractured femurs. Eighteen survivors and five non-survivors sustained knee injuries. Only eighteen surviving passengers and six non-surviving passengers had no injury to the lower limbs and pelvis.

Lower Extremity Injuries - Thirty one survivors and thirty eight non-survivors sustained lower leg fractures. Twenty six survivors and twenty four non-survivors sustained fractures/dislocations of the ankle. Twenty two survivors and six non-survivors sustained fractures of the bones of the feet. Many of those affected suffered fractures of more than one area.

Post crash entrapment - Following the impact the majority of the passengers were trapped, due to injury, seat failure or debris from overhead. Only 14 of the passengers were able to make a significant contribution to effecting their own escape. (AAIB, 1990)

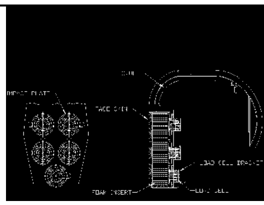
Although the Kegworth crash produced significant fatalities, the number of survivors gives testament to the significant advances in aircraft crashworthiness, survivability and fire safety. The increased survivability provided by these advances presents opportunities for further research in safety and restraint systems, injury mitigation and post-crash mobility for egress.

Upon reviewing the injury data from the Kegworth crash, it is clear that the Hybrid II and III dummies are not capable of measuring injury in several of the most important areas. The THOR dummy has been designed with greatly enhanced injury sensing capability in the regions of the face, neck, thorax, lower abdomen, pelvis / femur and lower extremities. The advances provided by the THOR dummy for sensing and assessing injury in these specific areas will be presented in detail below. Although the Kegworth accident report indicated a high number of injuries to the chest and shoulder regions, which could be accurately assessed using THOR's enhanced design of these regions, they will not be focused on in this paper.

FACE

In an aircraft seating environment, the passenger’s face can impact several hard surfaces including the forward seat back, the  tray table or structural elements of the aircraft, such as the window frame. From the Kegworth crash sited above, many of the passengers suffered severe head and facial trauma which could be assessed through testing with the THOR dummy.

**Figure #3** presents a drawing of the head/face design developed to meet this need.



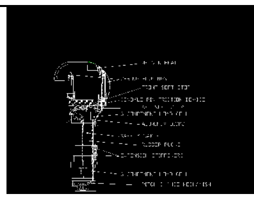
The THOR face structure design was based on the head/face structure developed by Melvin and Shaw (1989). The Melvin design was further improved with new instrumentation and a reusable load distribution element. In the THOR design, the face structure is separated for the purposes of injury assessment into five distinct regions: left and right orbital regions (eye sockets), left and right Maxillae (upper jaw bones) and Mandible (lower jaw bone). Unidirectional load cells are provided to measure the direct impact load applied to each region. Soft tissue over each region is represented by a reusable foam and rubber cushion assembly. The impact stiffness of the foam and rubber cushion has been selected to match human impact loading characteristics. The entire face is covered with a thin urethane skin which holds the foam cushion in front of the load cells, while allowing easy access for inspection and replacement of the foam. In order to preserve the correct loading characteristics, the foam inserts need to be replaced after every four tests involving facial loading. It is believed that this representation of the human face permits the proper response to facial impact, and permits accurate assessment of the potential for facial fracture injuries.

## MULTI-DIRECTIONAL NECK

The NHTSA has been investigating the requirements for and approaches to mechanical simulation of the human neck for several years. The development of a multidirectional neck - that responds in a human like manner from any direction of impact - has become increasingly important in the past several years with the interest in offset, rear and roll over crash testing for automotive safety engineering. In the aircraft seating environment, a multidirectional neck would be needed to properly evaluate side facing seats as well as offset impacts. As cited in the Kegworth example, nearly one-half of the non-survivors suffered injury to the neck structure.

As part of the THOR development program, GESAC was tasked by NHTSA to redesign the neck (based on a prototype developed by VRTC) so that it could be incorporated within the advanced frontal dummy. Since it was necessary to improve the dynamic response of the neck prototype developed by VRTC to meet the design objectives, a number of computer simulations were conducted to investigate changes that would improve the neck kinematic response in the three directions. These simulations were conducted using DYNAMAN, a lumped mass, 3-D occupant simulation model developed by GESAC. The THOR neck assembly underwent several testing series and revisions before arriving at the final design. A paper describing the analysis, design, and testing program used to evaluate the THOR neck assembly was presented by White, et al. (1996). The final design is presented in **Figure #4**.

Compression springs were located in the fore and aft regions of the skull to simulate the effects of musculature and correct head motions in the frontal flexion and extension directions. Rubber soft stops were attached at the base of the neck to help achieve the desired bending characteristics in both fore and aft motion. The neck assembly is made from a series of aluminum disks and rubber pucks which are bonded together using an epoxy resin system. The rubber pucks are elliptically shaped to provide the desired lateral bending response for the neck assembly. A pitch change mechanism was included at the base of the neck to permit initial placement of the neck in desired orientation. The instrumentation for the new neck assembly includes a pair of miniature load cells to measure the compression at the fore and aft spring locations. Six component Denton load cells at the top and base of the neck to measure the forces and moments developed at these locations.  A rotary potentiometer is used at the condyle pin to measure the relative rotation between the head and neck.

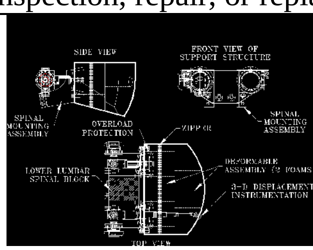


LOWER ABDOMINAL REGION

The need for accurate injury assessment of the soft tissue region in the lower abdominal region is very important for both automotive and aircraft crash research. The lower abdominal region is likely to be severely loaded in an aircraft crash, since the lap belt is used as the primary passenger restraint. Using the Kegworth example, over 75% of the fatalities suffered abdominal trauma, indicating that injury assessment in this body region is critical to aircraft safety research.

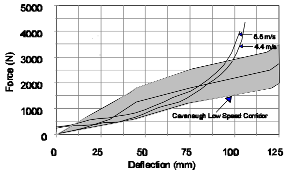
In the past fifteen years, many approaches have been taken to improve the loading and injury assessment capabilities of the crash dummy’s abdominal region. The Hybrid III incorporates an uninstrumented soft foam-filled bladder to represent the abdominal region. In order to detect lap belt or steering assembly intrusion into the abdomen, the TAD-50M design replaced the Hybrid III bladder with a shaped crushable Styrofoam block that acted as a witness plate. Measurement of the amount of residual Styrofoam crush was to provide indication of injury potential. Since both compression and velocity of compression were believed to be necessary for abdominal injury assessment, a new design approach was necessary.

The abdomen design developed for THOR has addressed the noted limitations in the Hybrid III and TAD-50M abdominal designs. The abdomen design has an upper and a lower unit. The upper unit is attached to the thorax through ribs 5, 6, and 7 and the lower unit fills the space between the lower ribs and the pelvis. Since the upper abdomen region is primarily associated with chest trauma, the lower abdomen is of primary interest for evaluating the lap belt restraint systems. The THOR lower abdomen assembly is shown in **Figure #5**. The basic design for the lower abdomen utilizes several layers of foam to simulate the load vs. deflection characteristics of the human abdominal tissue under impact. The foam structural elements of this assembly are enclosed within a durable Cordura cover. The cover has a zipper to provide access to the instrumentation and foam for inspection, repair, or replacement. The instrumentation



consists of two DGSP (double-gimballed string pot) assemblies, similar to those used in the TAD-50M thorax. The THOR units have been redesigned to increase the range of travel and updated with precision potentiometers that maintain calibration for a long series of tests. The
DGSP assemblies allow measurement of three-dimensional deflections at two distinct points. Deflections are calculated via a dedicated algorithm, utilizing the three potentiometer outputs. It is noted that the signals obtained from this instrumentation assembly during impact loading are sufficiently smooth that differentiation of the calculated displacements to velocity is feasible. Overload protection is provided to protect the instrumentation if compression of the abdomen exceeds approximately 114 mm. The abdomen assemblies have been extensively tested, and have been shown to maintain geometric and structural integrity under repeated impact loading.

The biofidelity of the lower abdomen assembly was compared to a series of experiments using cadavers performed in 1986 by Cavanaugh, et al., which reported the force deflection characteristics of the lower abdomen due to impacts using 1" diameter circular rods. These experimentally measured characteristics were selected as THOR design targets. A similar setup was used during the evaluation of the THOR lower abdomen assembly. **Graph #1** shows the measured force-deflection characteristics of the abdomen at two different impact speeds. The experimental results presented show that the abdomen response stays within the corridor of human response as defined by Cavanaugh up to approximately 100 mm of deflection. The deviation from desired response for deflections greater than 100 mm is not considered to be a serious issue, since abdominal deflections greater than this amount represent very high injury probability.




**GRAPH 1**

FEMUR, PELVIS AND KNEE COMPLEX

The femur, pelvis and knee complex represents a critical assembly of any crash test device because of the complex geometries and multiple loading conditions which may be encountered. The need for biofidelic loading and injury assessment of this assembly is evident in the data from the Kegworth crash in which 25% of the passengers suffered pelvis injuries, 25% sustained femur fractures and 18% sustained knee injuries. Clearly, this region of the crash test dummy needs to be well instrumented for accurate injury assessment during safety research testing.

The THOR pelvic assembly was designed based on the geometry defined by Reynolds (1981) in a study conducted for the Civil Aeromedical Institute of the FAA on the mid-sized male pelvis. All of the key anthropometric landmarks have been maintained in the pelvic structure. The pelvis / upper femur assembly was changed from the molded 90 degree assembly, seen in the Hybrid III dummy, to a "sit/stand" design, with revised flesh segmentation as defined by McConville (1980). **Figure #6** presents a drawing of the pelvic structure that has been designed for THOR. The femur assembly is attached to the pelvic structure through a pair of the standard Hybrid III ball joints. In addition, the flesh material and flesh mold were designed to more closely duplicate human compression characteristics and improve the representation of human/seat interaction than previous dummy designs. The compliance of the skin required to accomplish this was determined from a number of tests conducted at GESAC in which the force required to compress the skin was measured using a number of different probe shapes. (White, 1997) The results show that the compliance of the THOR pelvic flesh is close to that of the

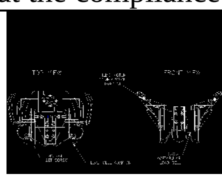


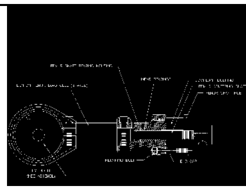
**FIGURE 6**

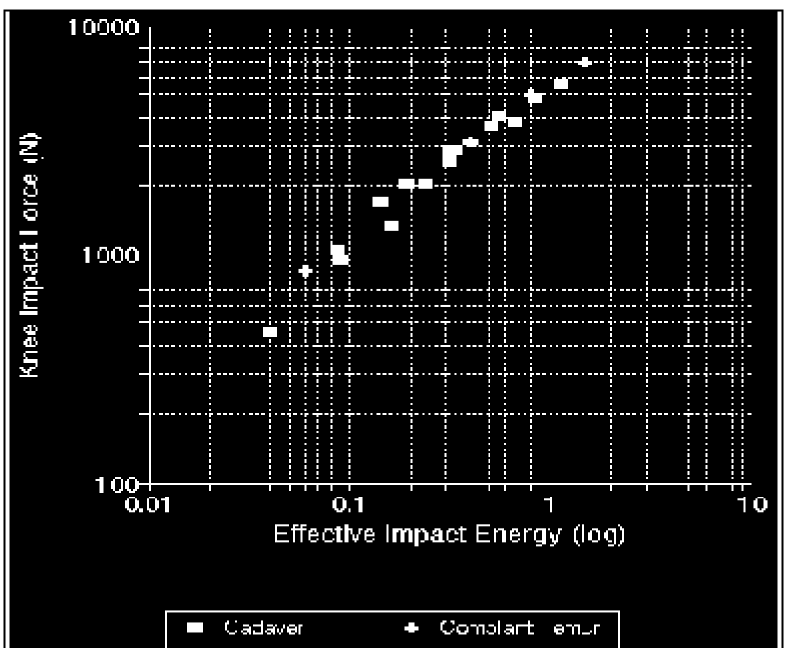
human and that of the Hybrid III is approximately six times stiffer. The seat/pelvic interaction of the THOR design should thus be significantly more human like than that of the Hybrid III, thus providing more accurate pelvis kinematics during crash testing.

The THOR pelvic assembly has been instrumented with a pair of triaxial acetabular load cells to measure the forces transmitted by each femur to the pelvis. In addition, a pair of compression load cells have been mounted in the Iliac notch region of the left and right pelvis wings. These compression load cells provide a direct indication of belt load, thereby allowing the test lab to determine if the lap belt was loading on the Iliac notches as desired. These load cells can also be used to indicate the condition of submarining in which the pelvis rotates and the belt slips off the bone structure into the soft tissue of the lower abdomen.

The THOR femur has been designed around a compliant section which was integrated into the femur shaft and tuned to improve the dynamic impact response of the knee. It had been determined that the knee loads for the previously used rigid femur (Hybrid III) greatly exceeded the loads measured on cadavers, particularly at the higher energy levels associated with severe impacts. **Figure #7** presents a drawing of the THOR compliant femur design. The compliant bushing is in line with the axis of the femur, and can be easily removed for certification or replacement. The standard Hybrid III knee is currently used in the THOR leg assembly. A standard six component Denton load cell is incorporated between the compliant femur element and the knee to measure femur loads and moments.

The biofidelity of the THOR knee / femur assembly was determined through comparison to a series of tests conducted in 1976 by Horsch and Patrick. These tests were performed on cadavers to determine the response of the knee and femur to impact loading parallel to the axis of the femur. The results presented in **Graph #2** are those obtained during the tests of the THOR femur on a fully assembled dummy and are compared to the cadaver test results obtained by Horsch and Patrick. As can be seen, the results obtained with the THOR femur closely fit the data obtained with the cadavers even at high energy levels. It is noted that at the highest energy level for which data was obtained, the knee impact force of the Hybrid III was approximately 40% higher than that obtained with the cadavers. This result demonstrates the effectiveness of the THOR compliant element in increasing the biofidelity of this segment.





10000
1000
100
0.01
0.1
1
10
Knee Impact Force (N)
Effective Impact Energy (log)
Cadaver


**GRAPH 2**

LOWER EXTREMITY

The development of an advanced lower extremity has been an ongoing project for the past several years. The lower extremity used in the Hybrid III dummy does not provide the desired the desired range of motion or joint torque characteristics required to meet the new standards proposed by NHTSA in 1998. In addition, the Hybrid III lower leg was only instrumented in the tibia section, and the assessment of injury to the foot and ankle was not possible. In the automobile environment, the interest in the evaluation of lower extremity injuries has recently increased. With the widespread use of seat belts and airbags, more people are surviving the major chest and head trauma only to experience a long recovery period in rehabilitating lower leg injuries. The frequency of lower extremity injuries in aircraft accidents is also high - as shown in the Kegworth example, over 50% of the passengers suffered lower leg fractures, nearly 40% of the passengers sustained fractures / dislocations of the ankle, and over 20% sustained foot fractures. The problem of lower extremity injuries in an aircraft is compounded by the fact that it severely hinders passenger evacuation; passengers that are likely to survive otherwise may become trapped in the plane.

In 1994, the NHTSA Vehicle Research and Test Center (VRTC), together with Applied Safety Technology Corporation (ASTC), began development of the ALEX (Advanced Lower Extremity) which would be used on the advanced frontal dummy to be developed. In 1997, GESAC pursued development of its own lower extremity for THOR, called THOR-LX, also under NHTSA direction. Both designs were tested and refined during the past year. Recently, GESAC and ASTC have combined their efforts to produce the final version of the THOR-LX which incorporates aspects from both designs. The final version of the THOR-LX can be seen in **Figure #8.**

The mechanical design of the THOR-LX provides several advances over previous lower extremity designs. A compliant section, similar to the THOR compliant femur section, was designed in the tibia shaft which provides the correct force transmission from the heel to the knee complex. A spring damper Achilles tendon system was designed to aid in producing the desired ankle motion and torque characteristics. The new ankle design provides the correct joint axes placement and correct torque vs. angle response for the two primary axes (dorsi / plantar-flexion and inversion / eversion) The range of motion in all three principal directions of rotation was increased to the specifications provided by NHTSA. Soft stop elements were used to provide human-like stiffness at the extremes of motion.

The THOR-LX was also updated with many new sensors to increase the ability of the dummy to measure injury and trauma. The standard upper and lower tibia load cells from Denton were incorporated into the design. These load cells provide the force and moment data for the tibia shaft. A load cell was implemented into the Achilles tendon housing which provides a direct measurement of the contribution of the Achilles to the overall ankle joint torque. Unidirectional load cells were placed at the heel and ball of the foot to directly measure contact forces in this region. Three rotary potentiometers were used to measure the rotation of the individual ankle joints, thereby providing complete kinematic data. Finally, a pair of triaxial accelerometers (one on the foot plate, and one on the tibia) were included to allow the transformation of the measured tibia moment to the calculated ankle moment.

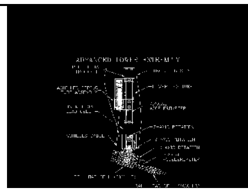


**FIGURE 8**

THOR TESTING AND EVALUATION

Since the THOR testing and evaluation program was initiated in 1995, the THOR dummy has been subjected to over one hundred full dummy sled tests and over one hundred twenty individual component tests. This testing was conducted in North America at the University of Virginia, DCIEM in Canada, and VRTC testing facilities. In addition, THOR has been extensively tested at several laboratories overseas including: the JARI (Japan), Volvo (Sweden), Autoliv (Sweden), TRL (England), TNO (Netherlands), and FORS/Autoliv (Australia). In general, the feedback and results from the testing laboratories have been very positive. The THOR dummy is now being circulated and tested worldwide, with the hope that it will find broad acceptance and use. Overall, THOR has been proven to be a very rugged, repeatable and biofidelic testing device.

## CONCLUDING REMARKS

It is believed that the development of THOR over the last four years has resulted in an anthropomorphic test device which offers significant benefits with respect to currently employed frontal test devices now in use for evaluation of automotive safety systems. It is also believed that the THOR design holds potential for application to aircraft safety system evaluation applications as well. The THOR design embodies significant improvements in body-segment response biofidelity, and incorporates an expanded array of specialized transducers selected for their relevance to crash environment injury mechanisms. THOR has also been designed with careful attention to "user-friendly" features. In summary, it is believed that THOR represents a significant advance in the world of crash testing and safety research.

## ACKNOWLEDGMENTS

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